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A NEW END TAB DESIGN FOR OFF-AXIS TENSION TEST OF COMPOSITE MATERIALS

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In high temperature environments, testing methods must be very simple. For fiber composites, the material principal axes can be varied with respect to the loading direction to produce different states of stress in reference to the material axes. Thus, using off-axis composite specimens, a number of mechanical properties can be determined using simple tension tests on off-axis specimens. The main difficulty in using off-axis tension specimens lies in the presence of shear-extension coupling when the specimen is mounted on rigid grips in material testing machines. In order to resolve this problem, we designed a new end tab for the off-axis composite specimens. The new end tab was fabricated using a fiberglass knit in a silicone rubber matrix, and was used in the off-axis tension tests on unidirectional composites. It was shown experimentally that this new tab allowed shear deformation of the specimen to occur in the hydraulic grips and, thus, produced a uniform state of strain in the specimen. Consequently, the shear modulus could be determined accurately using this new tab. Furthermore, due to the absence of stress concentrations, this procedure could also be used to determine shear strength.

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PREFACE

The High Temperature Materials - Mechanical, Electronic and Thermophysical Properties Information Analysis Center (HTMIAC) is a U.S. Department of Defense (DoD) Information Analysis Center sponsored by the Office of the Undersecretary of Defense Research and Engineering. It is operated by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana 47906, under the Defense Logistics Agency (DLA) Contract DLA900-86-C-0751. The DLA contract is awarded to Purdue by the Defense Electronics Supply Center (DESC), Dayton, Ohio 45444-5208, with Ms. Sara M. Williams as the Contracting Officer.

HTMIAC is under the technical direction of Mr. Jerome Persh, Office of the Undersecretary of Defense Research and Engineering, Attn: OUSDR&E (R&AT)(MST), Pentagon, Room 3D1089, Washington, D.C. 20301-3081 and Dr. Jim C. I. Chang, Naval Research Laboratory, Code 6330, Washington, D.C. 20375-5000. HTMIAC is under the program management of Mr. Paul M. Klinefelter, the Defense Technical Information Center (DTIC), Attn: DTIC-DF, Cameron Station, Alexandria, Virginia 22304-6145.

HTMIAC serves as the DoD's central source of data and information on high temperature materials properties, especially the properties of aerospace structural composites and metals and of infrared detector/sensor materials. It supports the DoD research and development programs and weapons systems in general, and supports the DoD Tri-Service Laser Hardened Materials and Structures Group (LHMSG) to meet the material property data requirements for high energy laser structural and detector vulnerability, survivability, and hardening assessments in particular. It also provides similar support to the DoD high energy laser community associated with the Strategic Defense Initiative (SDI) programs.

To fulfill its assigned mission to support the DoD, HTMIAC performs both its basic operation and special studies/tasks. The work detailed in this technical report constitutes a part of one of the tasks of a special study entitled "Thermophysical and Mechanical Properties of Composite Materials under Rapid Heating Conditions" sponsored by the Defense Nuclear Agency (DNA), Washington, D.C. 20305-1000, through DNA MIPR 85-658. The DNA Program Manager is Captain Gilbert Wendt, Attn: DNA-SPAS.

This particular task of the Special Study was performed by the Composite Materials Laboratory (CML) of the School of Aeronautics and Astronautics of Purdue University under the supervision and technical administrative support of HTMIAC. Well known in this country and abroad, the Composite Materials Laboratory at Purdue is one of the best research laboratories on composite materials in the United States.

C. Y. Ho
Director
HTMIAC and CINDAS

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INTRODUCTION

In today's competitive aerospace and military industry weight and strength are of critical importance. This has led to the widespread use of various different types of long fiber composite materials. In order to take full advantage of the weight savings offered by composites, it is necessary to have an accurate understanding of the individual laminate properties. Both material constants and the ultimate strengths are of importance.

There are a number of different test methods currently being used to obtain shear properties of composite materials. Four of the commonly accepted tests are torsional tubes, rail shear tests, $[+-45]_s$ coupon tests, and off-axis coupon tests. Each test has its own advantages and disadvantages. Torsional tubes allow accurate measurement of the shear stress strain relationship, but are extremely expensive to fabricate and require special test equipment. Rail shear tests have a number of disadvantages: it is very hard to produce a pure shear over the test section, and the test fixture introduces large stress concentrations. Coupon tests of the $[+-45]_s$ specimen also have problems due to the fact that a state of combined stress rather than pure shear exists in such a laminate and that it is very difficult to detect the first ply failure and to avoid lamination effect on the ply strength.

The fourth test method uses off-axis coupon specimens of unidirectional composite [1-5]. This method seems ideal: easy specimen fabrication, very simple data reduction, requiring no special equipment. In order to extract the material constants from an off-axis test, it is assumed that a uniform state of both stress and strain exists throughout the test section. One problem with off-axis tests of unidirectional composites is the extension-shear coupling resulting

from the anisotropic material behavior [6-7]. Figure 1(a) shows the deformed state of an off-axis specimen subject to uniaxial tension. If the ends are constrained to remain horizontal through the use of rigid clamps, both shearing forces and bending moments are introduced as shown in Fig. 1(b). These induced forces and moments produce a nonuniform strain field which is not suitable for measuring the basic material properties. The stress concentrations near the grips make it unsuitable for measuring the strength properties using off-axis specimens. Figure 2 shows the coefficient of mutual influence for three different composite materials. For graphite epoxy systems the most prominent extension-shear coupling occurs between 10 and 15 degrees.

To minimize the stress concentration effect, specimens of large aspect ratios 12 to 15 are recommended. Alternatively, Richards & Airhart [2] and Pipes & Cole [3] suggested using very long tapered fiberglass tabs. These long tapered tabs redistribute the load gradually and may reduce the high stress concentrations at the clamps. This method of using long tapered tabs still results in stress concentrations, although not as severe as in the case of short nontapered tabs. Fabrication becomes very time-consuming and expensive when using such tapered tabs.

Chang, Huang, and Smith [8] perfected a pinned-end-test frame and compared test results obtained using it with results from rail shear tests and from standard clamped 10 degree off-axis tests. The pinned specimen resulted in higher ultimate shear stress and shear strain values than either of the other types of tests. These results suggest that the pinned-end construction produces a more uniform state of stress. Although the pinned test helps obtain more accurate material properties, the method is very inconvenient. A special load frame is required and a great deal of care must be taken in aligning the specimen. Finite

element results obtained by Rizzo [6] also show that the pinned specimen has large stress concentrations which could cause premature failure and inaccurate representation of the true strength properties.

In this paper a new tab design using fiber-glass fabrics embedded in a silicon-rubber matrix was investigated. This new tab allows the use of rigid grips on most material testing machines to achieve a state of uniform stress in off-axis composite coupon specimens.

NEW TAB DESIGN

Selection of Tab Materials

The high stress concentrations and nonuniformities throughout the stress field in off-axis tests are caused by the restriction of shear deformation. In order to solve the problem the load must be applied in a way which allows shear deformation. A tab in between the specimen and grip which allows shear deformation would solve the problem. A number of different compliant materials which offer very low shear rigidity came to mind as possible solutions. Unidirectional composites, soft adhesive layers, and rubber tabs were all tried with poor results.

Tests preformed with various soft tab materials brought to light another problem. The tab must be very stiff transversely or the grips tend to crush the unidirectional coupons. An orthogonally woven fiberglass cloth exhibits all the desired characteristics. Cloths have high transverse and longitudinal stiffness with very little shear rigidity. With this in mind two different types of fiber-glass cloths were molded into a soft matrix of siliconerubber.

The first type of fiberglass cloth tried was a standard industrial grade cloth used in automotive repair. The second material was a type of knit available from King Fiberglass Corporation. This knit consists of a layer of unidirectional fiberglass laid transversely over another layer of unidirectional fiberglass and knit together using polyester thread. Knits are available in different weights allowing the tabs to be tailored to the application. A bi-directional knit of 18.17 oz/sq-yd composed of E-glass fibers was used in the study. The weft is 8.96 oz/sq-yd while the warp is 8.81 oz/sq-yd. Polyester yarn of .404 oz/sq-yd is used to knit the two layers together. Both weft and warp have a tensile modulus of 10.5 msi.

Fabrication Procedure

The matrix material was composed of a heat cured silicone rubber compound produced by General Electric. It consists of a liquid rubber compound titled RTV664A and a separate curing agent RTV664B. The curing agent was mixed as stated in the manufacture's instructions.

Twelve inch square panels were fabricated using the silicone rubber and fiberglass cloth. The fabrication procedure was very similar to that of a graphite-epoxy panel. A layer of release ply was laid onto a tool plate. The fiberglass was then cut and laid over the release ply. Four ounces of silicone rubber were then mixed and spread evenly over the cloth. A second layer of release ply and a caul plate were placed over the panel. The panel was then placed in a vacuum bag and put into an autoclave to cure. The resulting panels had a nominal thickness of .040 inches. The deviations in thickness were kept within .005 inches.

Material Characterization

The material properties of the fiber-glass silicone rubber panel were determined after the new tabs achieved success in producing a uniform strain field in the off-axis composite specimen. The goal was to find the material properties necessary to allow shear deformation under the tab. The longitudinal modulus was determined using a coupon specimen. The shear modulus was measured indirectly using a coupon specimen cut from the panel at 45°-dissection to form a [±45] laminate. The results presented in Table 1 indicate the ratio of the longitudinal stiffness to in-plane shear stiffness for the silicone rubber fiberglass knit tabs is on the order of 1000:1. In a graphite-epoxy material system this ratio is around 26:1. Much higher ratios of stiffness should be obtainable by using a graphite knit instead of fiberglass. A graphite material system would also improve strength and thus allow higher loads to be achieved by the tabs.

EXPERIMENTAL PROCEDURE

All specimens were fabricated out of 8 plies of Hercules AS4 3501-6 and were cured, with peel ply on both sides, according to the manufacturer's instructions. As shown in Fig. 3, on each specimen are mounted 8 Micro Measurements EA-13-125AC-350 strain gages. Four gages are mounted on the front and four duplicate gages are mounted on the back in order to eliminate bending errors in the data acquisition.

Each coupon was placed in an MTS 810 material testing system. The specimen was then gripped in MTS 647 hydraulic wedge grips under 600 lbs pressure.

The panels fabricated out of fiber-glass and silicone rubber were cut into 1x1.5 inch tabs. The tabs were then placed on the test coupons and secured in place with a thin band of tape. Several glues were tried with no success. All the glues tried failed to form a proper bond with the smooth surface of the silicone rubber. Care must be taken to properly align the tabs with the specimen to achieve the best results. The fiberglass knit tabs must be placed on the specimen with the transverse fiber direction next to the specimen. This placement is required to minimize crushing after securing in the hydraulic grips. The tab composed of silicone rubber and fiberglass was not capable of achieving extremely high loads. During the test it was found that the tab could transmit loads up to 1500 lbs. Loads higher then this resulted in the fiberglass knit failing and thus the specimen slipped out of the grips. Much better results should be obtained using a heavier knit or a graphite knit.

RESULTS ON STRESS CONCENTRATION

The 10° off-axis specimen was used to evaluate the new tab. The specimen geometry is given in Fig. 3.

For comparison purposes, the conventional glass/epoxy tabs were also used. The longitudinal strains at the four strain gage locations are presented in Fig. 4. The finite element solutions obtained by assuming clamped boundary conditions are also shown in this figure. The large stress concentrations near the grips are clear (see gage 1 and gage 2). The good agreement between the experimental data and finite element solutions indicate that the conventional glass/epoxy tab produces a rigid boundary condition.

Figure 5 presents the strains for the 10° off-axis specimen at the four gage locations. The specimen gage length was 6 inches. It is evident that a state of uniform strain (thus uniform stress) was achieved.

In order to study the tab's capabilities shorter specimens of 4 inch and 3/4 inch gage lengths were used. Figures 6 and 7 show the results for 10 degree off-axis coupons. In both cases the tab produced very good results. These results show that by using the new fiberglass siliconerubber tab it is not necessary to use a large aspect ratio to achieve a uniform state of strain.

One might surmise that the reason the new method could achieve a uniform strain field might be the result of slipping between the tab and specimen due to the lack of a good bond between the two surfaces. In the test, no slipping was observed between the tab and the specimen. To prove that it is the tab material properties but not slipping which is responsible for the success achieved, further experiments were conducted. A series of tests were preformed using conventional rigid fiber-glass epoxy tabs. These tabs were placed on to the 6 inch specimen without bonding. Figure 8 shows that the free epoxy fiberglass tabs produced poor results. The results from this series of tests are similar to those produced when tabs were bonded to the specimen. Slipping between the tab and specimen, therefore, cannot be used to explain the success achieved with the new tabs.

SHEAR MODULUS

Off-axis specimens can be used to measure the in-plane shear modulus G_{12} using rosette strain gages [9]. The specimen geometry used in this measurement is shown in Fig. 9.

Two different methods were used to obtain the shear modulus. The first is an off-axis specimen tested at various fiber orientations. Each orientation is tested using both standard fiberglass epoxy tabs and the new tabs developed in this paper. Results from the off-axis tests are compared to a value of shear modulus obtained from a coupon test of a $[+-45]_{2s}$ laminate.

From the longitudinal gage, the longitudinal strain was obtained, and the apparent Young's moduli for 10° and 20° off-axis specimens were determined. The results are presented in Table 2. It is seen that there is little difference between the results using the conventional tab and the new tab. This finding, of course, is not surprising as the longitudinal gage is located along the center line of the specimen and, thus, is not affected by the bending moment and shear force induced by the grip constraints.

In order to determine the in-plane shear modulus using a unidirectional off-axis composite specimen, it is necessary to simultaneously monitor the applied stress and the resulting strains in the three strain gage directions. Let x_1 and x_2 be the material principal directions, respectively. Then using the coordinate transformation law, we have

$$\sigma_{12} = -\frac{1}{2}\,\sigma_{xx}\sin 2\theta \tag{1}$$

$$\gamma_{12} = (\epsilon_{yy} - \epsilon_{xx})\sin 2\theta + \gamma_{xy}\cos 2\theta \tag{2}$$

The strains measured from the rosette are denoted by ϵ_1, ϵ_2, and ϵ_3, respectively (see Fig. 9). Thus,

$$\epsilon_{xx} = \epsilon_1 \ , \ \epsilon_{yy} = \epsilon_3 \ , \ \gamma_{xy} = 2\epsilon_2 - \epsilon_1 - \epsilon_3 \tag{3}$$

Using Eqs. (1-3), the shear stress-strain can be established based on the experimental data.

Since there is no extension-shear coupling in a $[+-45]_{2s}$ laminate, the conventional tab was used in the test. The $[+-45]_{2s}$ laminate is a special laminate from which the lamina in-plane shear modulus can be calculated from the measured longitudinal strain ϵ_{xx} and the transverse strain ϵ_{yy} as [10]

$$G_{12} = \frac{\sigma_{xx}}{2(\epsilon_x - \epsilon_y)} \tag{4}$$

The shear moduli obtained using the three procedures are presented in Table 3. The results from using $[+-45]_{2s}$ laminate and off-axis specimens with the new fiberglass knit tab yielded a shear modulus approximately equal to 1×10^6 psi. The shear modulus obtained from the $10°$ off-axis specimen with the conventional glass/epoxy tab is significantly higher. A similar trend was also reported by Daniel [11]. This could be due to the fact that, in such a case, shear stress exists throughout the $10°$-off-axis specimen. Consequently, the measured ϵ_2 strain is quite different from that for the assumed uniform tension case. Note that at the mid-span of the specimen, the indirect bending moment is vanishing and hence, ϵ_1 and ϵ_3 should not be affected by the induced shearing and bending.

SHEAR STRENGTH

The 10^0– and 20°–off-axis specimens were tested to determine the effect of the new tab on measuring the ultimate strength. Of the sixteen specimens for each orientation used for testing, eight specimens were tested using fiberglass epoxy tabs while the others were tested with the new silicone rubber knit fiberglass tabs. Each specimen had a net gage section 1-inch wide and 8-inches long. The test data for all the specimens are listed in Table 4. It is evident that the use of the new tab significantly increased the ultimate strength. Note that the 10_0 specimens produced much less scatter in strength than the 20° specimens.

Besides increasing the ultimate shear strengths, the new tabs also alter the location of failure in the 10°- and 20°- specimens. Specimens tested with conventional fiberglass epoxy tabs consistently failed along the fiber, with the initial failure occurring at the high stress concentration site, i.e., the edge of the tab. Specimens tested using the new tab failed along the fiber, but the failure occurred randomly throughout the test section. This random pattern of failure indicated that the tab produced a uniform stress field throughout the test section.

A state of pure shear relative to the material principal axes cannot be produced using off-axis specimens. Direct determination of the shear strength is not possible. An indirect method using the Tsai-Hill [9] failure criterion was used to calculate the ultimate shear stress.

The Tsai-Hill criterion is given by

$$(\frac{\sigma_{11}}{X})^2 - (\frac{\sigma_{11}}{X})(\frac{\sigma_{22}}{X}) + (\frac{\sigma_{22}}{Y})^2 + (\frac{\sigma_{12}}{S})^2 = 1 \qquad (5)$$

where X, Y, and S are the longitudinal, transverse, and shear strengths, respectively. In separate tests, the longitudinal strength and transverse strength

were obtained as X = 310 ksi and Y = 8.2 ksi, respectively [12]. Using these values and the Tsai-Hill criterion, the shear strength was calculated and listed in Table 5. The shear strength obtained using the conventional tab is significantly lower than that using the new tab. The lower strength associated with the conventional tab is, of course, due to the effect of stress concentration near the tab.

CONCLUSION

A new end tab fabricated of fiberglass knit and a compliant silicone rubber matrix allowed shear deformation to occur in off-axis composite specimens clamped by hydraulic grips. This capability enabled the off-axis specimen to achieve a uniform strain field and, thus, is suitable for characterization of mechanical properties of unidirectional composites. Further, the new tab design makes it possible to use short specimens for testing without inducing the undesirable stress concentration effect produced by the conventional rigid tab.

Although shear strength must be determined by using a failure criterion when off-axis specimens are used, the procedure is not sensitive to the other strength values (longitudinal and transverse strengths) used when small off-axis angles are selected. Moreover, if a failure theory is to be used in general failure analyses, this procedure will allow the shear strength to absorb whatever inherent inaccuracy the failure criterion has and yield an accurate overall strength prediction.

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Table 1 Properties of Tabbing Materials

Material	E_1	ν_{12}	G_{12}	E_1:G_{12}
Fiberglass Knit Tabs	0.60 msi	0.20	0.71 ksi	845:1
Fiberglass Cloth	0.30 msi	0.50	2.80 ksi	107:1

Table 2 Comparison of Apparent Stiffness Modulus (msi)

Fiber Orientation	Fiberglass Epoxy Tabs	Fiberglass Silicone Tabs
10 degrees	13.45	13.80
20 degrees	6.56	6.80

Table 3 Comparison of Shear Modulus (msi)

Fiber Orientation	Fiberglass Epoxy Tabs	Fiberglass Silicone Tabs
10 degrees	1.25	.95
20 degrees	1.07	1.08
$[\pm 45]_{2s}$	1.00	-

Table 4 Ultimate Stresses of Off-Axis Specimens

	Conventional Tabs		New Tabs	
Specimen	Load (lbs)	σ_x (ksi)	Load (lbs)	σ_x (ksi)
10 degrees	1109.	55.48	1313.	65.66
	1214.	60.70	1340.	67.00
	1218.	60.90	1387.	69.35
	1232.	61.64	1402.	70.08
	768.	38.40	1225.	61.28
	1010.	50.50	1274.	63.70
	1096.	54.81	1279.	63.97
	1121.	56.09	1316.	65.79
Average	1104.	55.19	1317.	65.85
	$(\frac{\sigma_{11}}{X})^2 = 0.0290$ $(\frac{\sigma_{22}}{Y})^2 = 0.0550$		$(\frac{\sigma_{11}}{X})^2 = 0.0440$ $(\frac{\sigma_{22}}{Y})^2 = 0.0730$	
20 degrees	302.	15.08	480.	24.02
	470.	23.52	482.	24.12
	522.	26.13	581.	29.05
	522.	26.13	703.	35.17
	374.	18.69	537.	26.87
	394.	19.70	626.	31.31
	411.	20.55	640.	32.02
	535.	26.77	656.	32.83
Average	441.	22.07	588.	29.42
	$(\frac{\sigma_{11}}{X})^2 = 0.0036$ $(\frac{\sigma_{22}}{Y})^2 = 0.1200$		$(\frac{\sigma_{11}}{X})^2 = 0.0064$ $(\frac{\sigma_{22}}{Y})^2 = 0.2200$	

X = 310 ksi

Y = 8.2 ksi

Table 5 Comparison of Ultimate Shear Strength

Fiber Orientation	Fiberglass Epoxy Tabs	Fiberglass SiliconeTabs	% Diff.
10 degrees	9.8	11.9	18
20 degrees	7.5	10.7	30

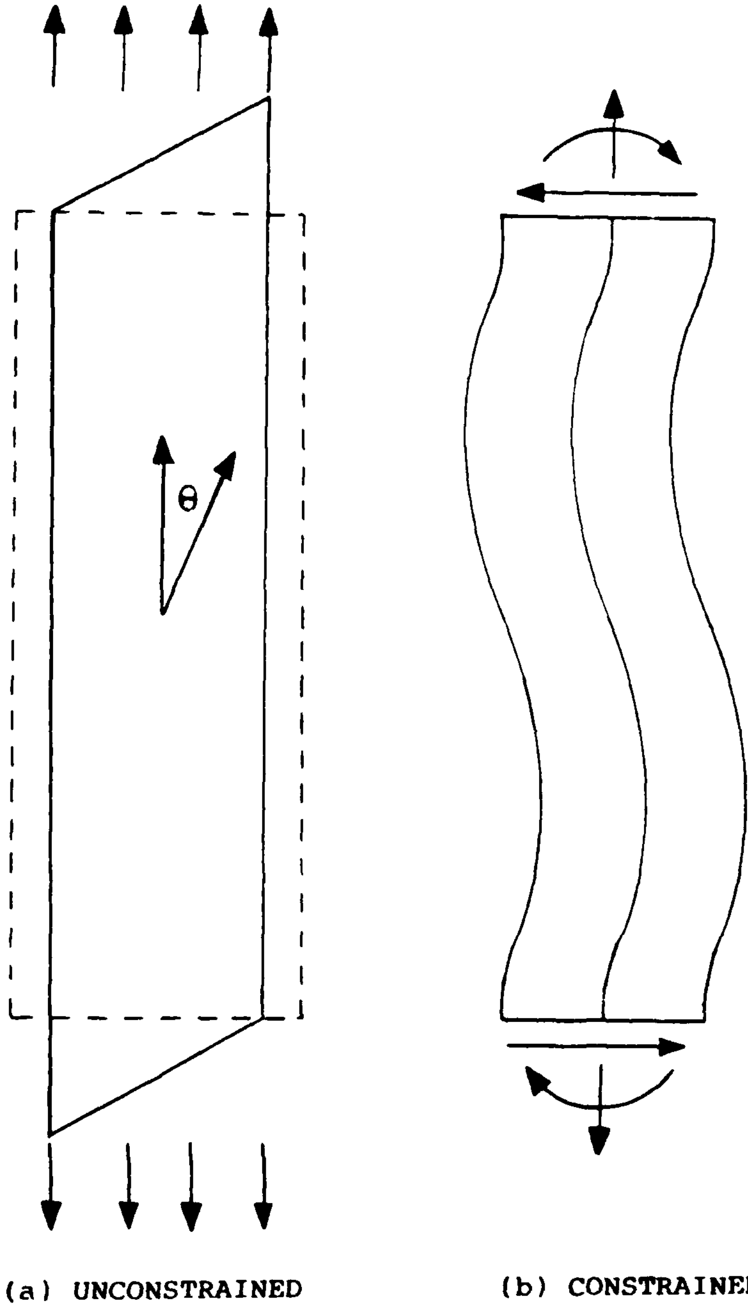

Figure 1. Unconstrained (a) and constrained (b) deformations in an off-axis composite specimen

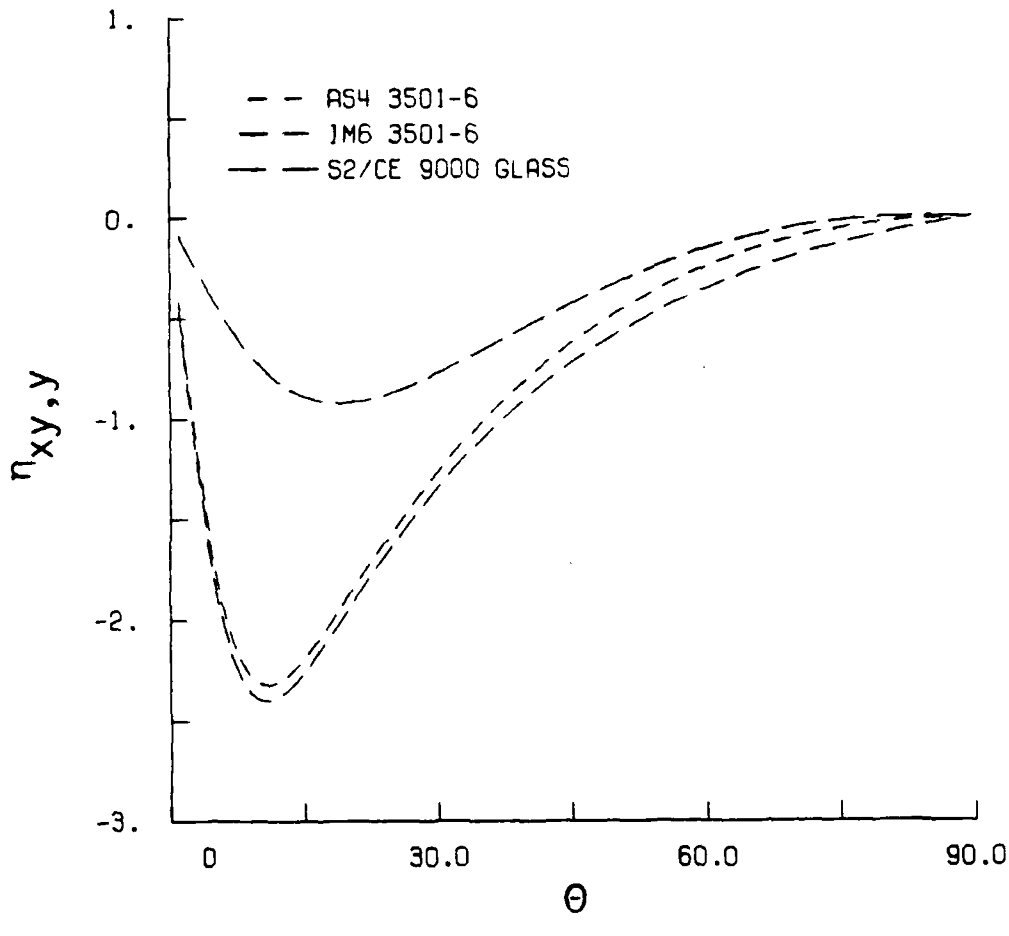

Figure 2 Extension-shear coupling for different composite materials

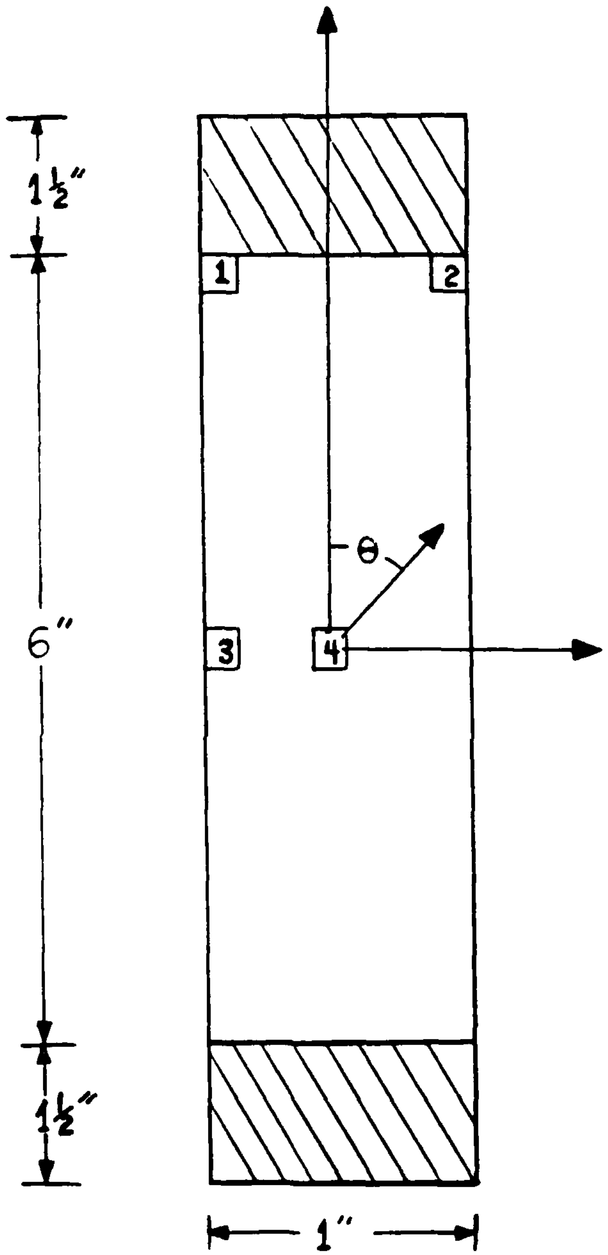

Figure 3 Specimen geometry (not to scale)

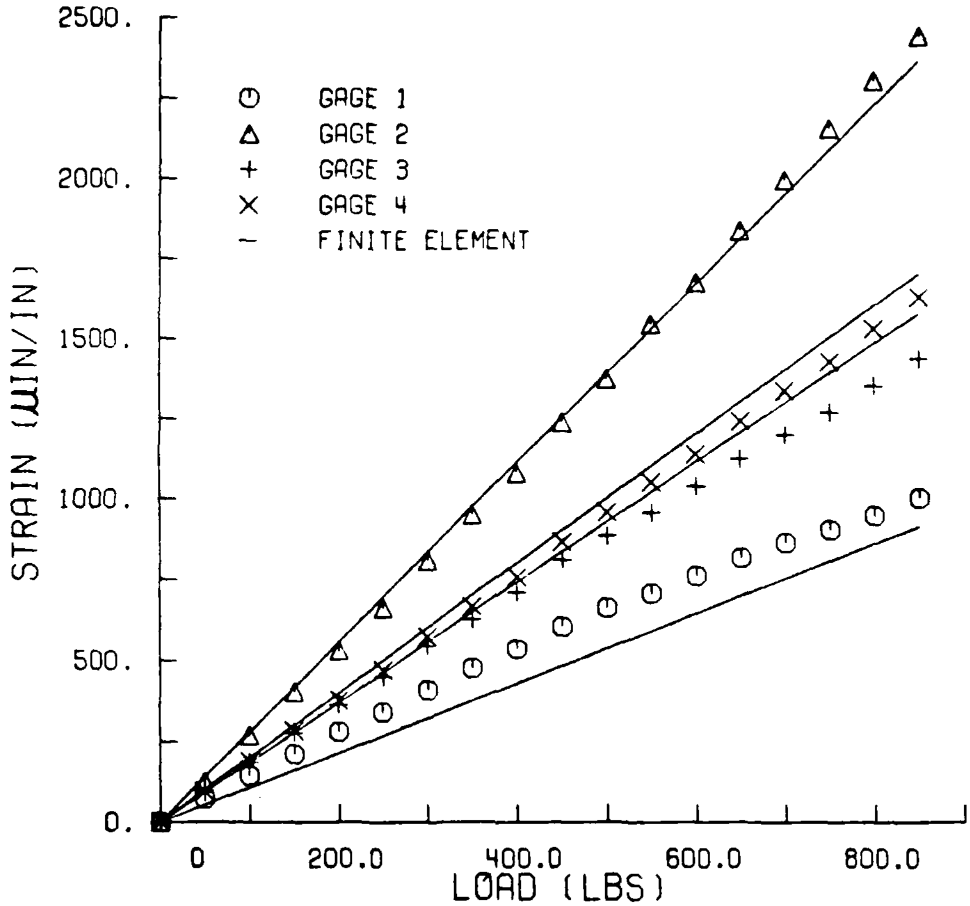

Figure 4 Comparison of finite element and experimental results for a 10° off-axis specimen using conventional glass/epoxy end tabs

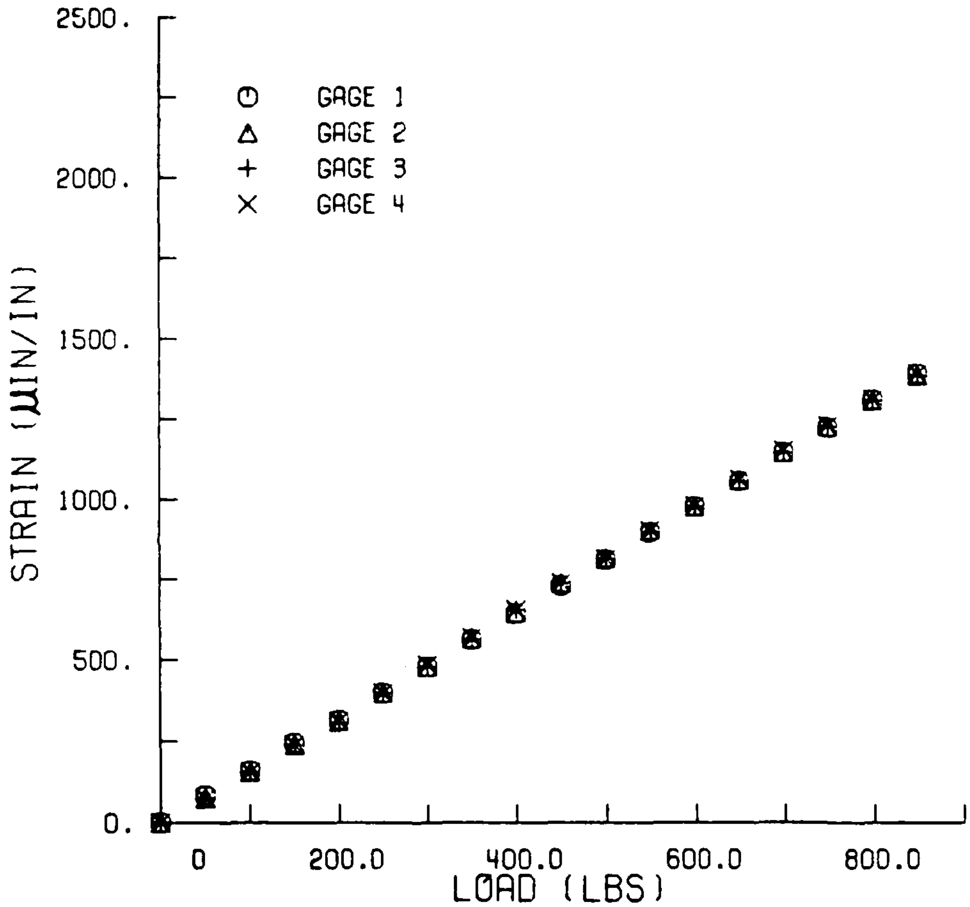

Figure 5 Strains at four locations in a 10° off-axis specimen using the new fiberglass knit tabs

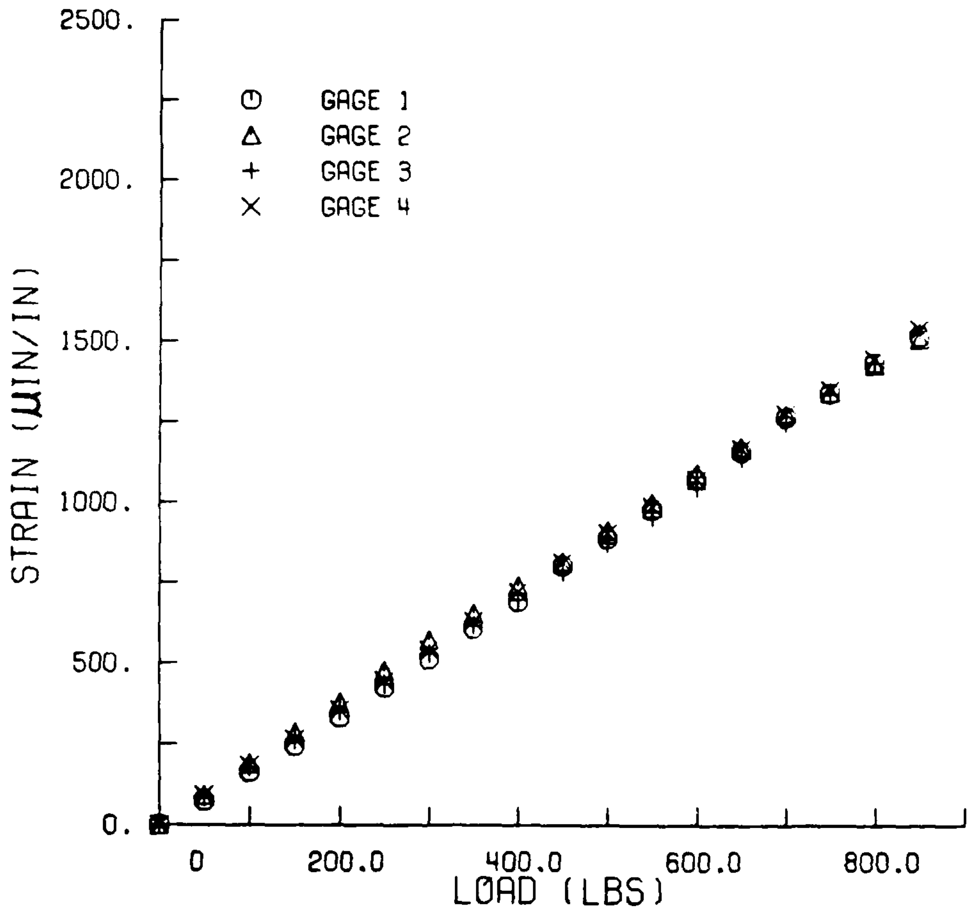

Figure 6 **Strains produced in a specimen with 4 inch gage length**

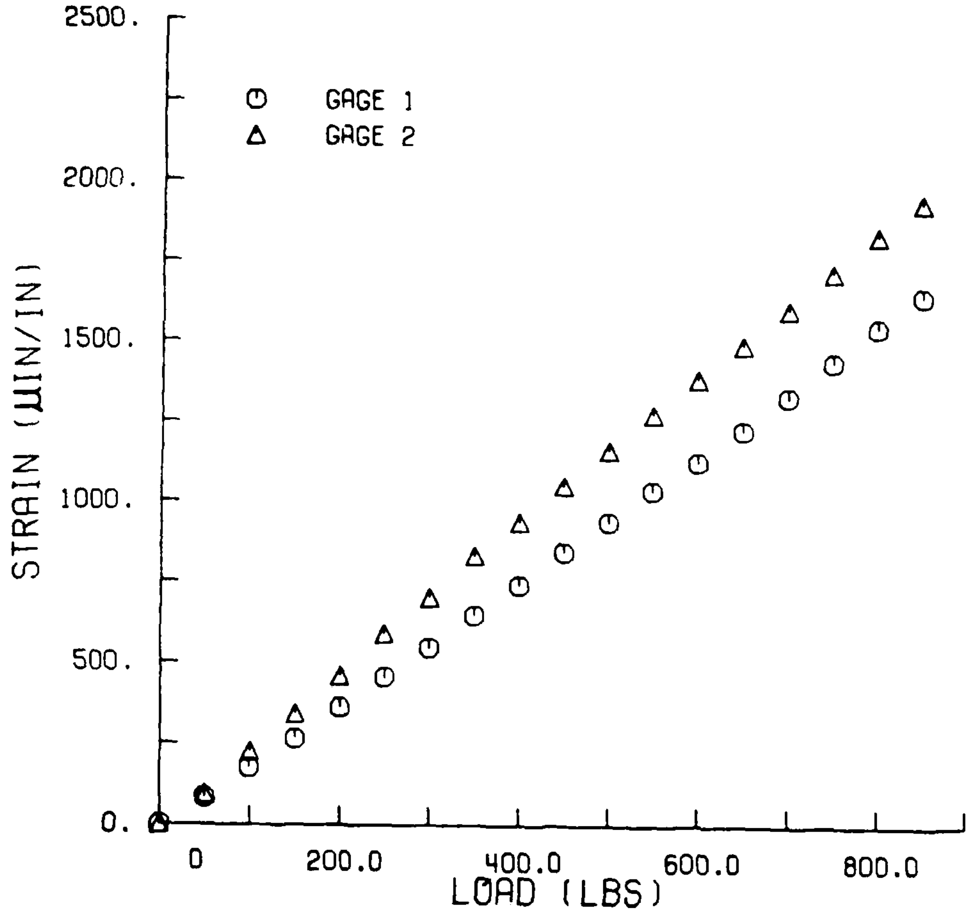

Figure 7 Strains produced in a 3/4 inch specimen

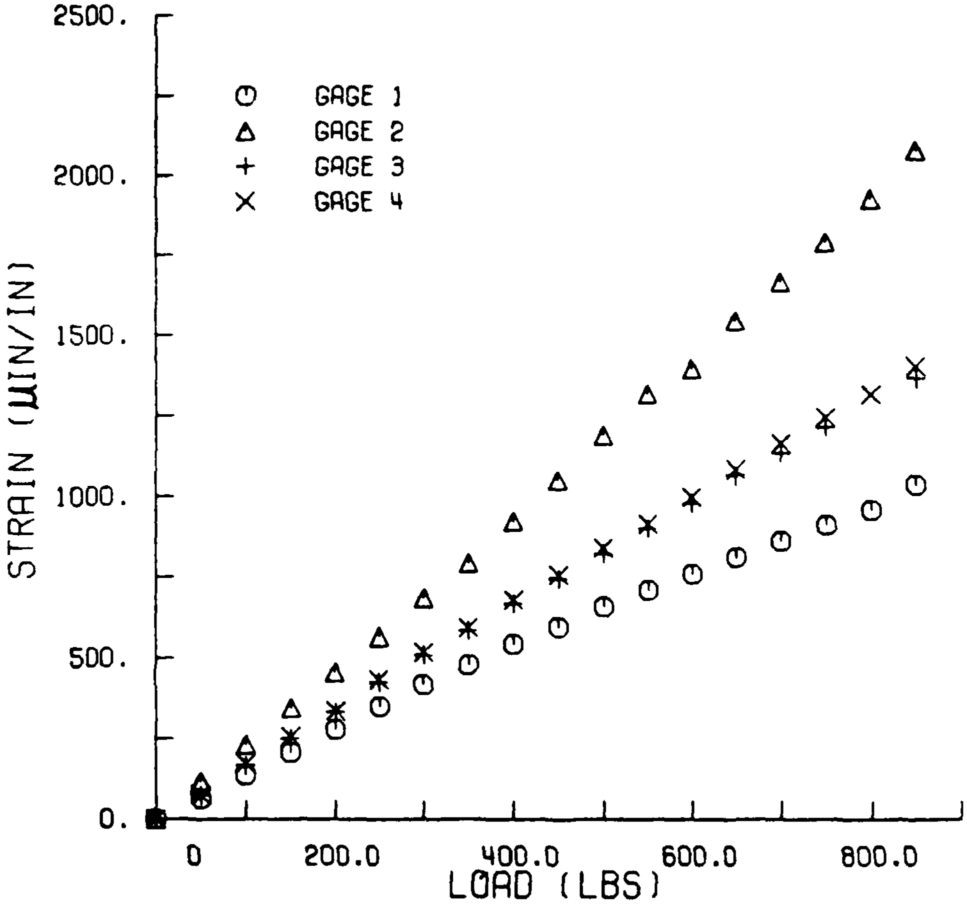

Figure 8 **Strains produced in a 10° off-axis coupon using unbonded fiberglass epoxy tabs**

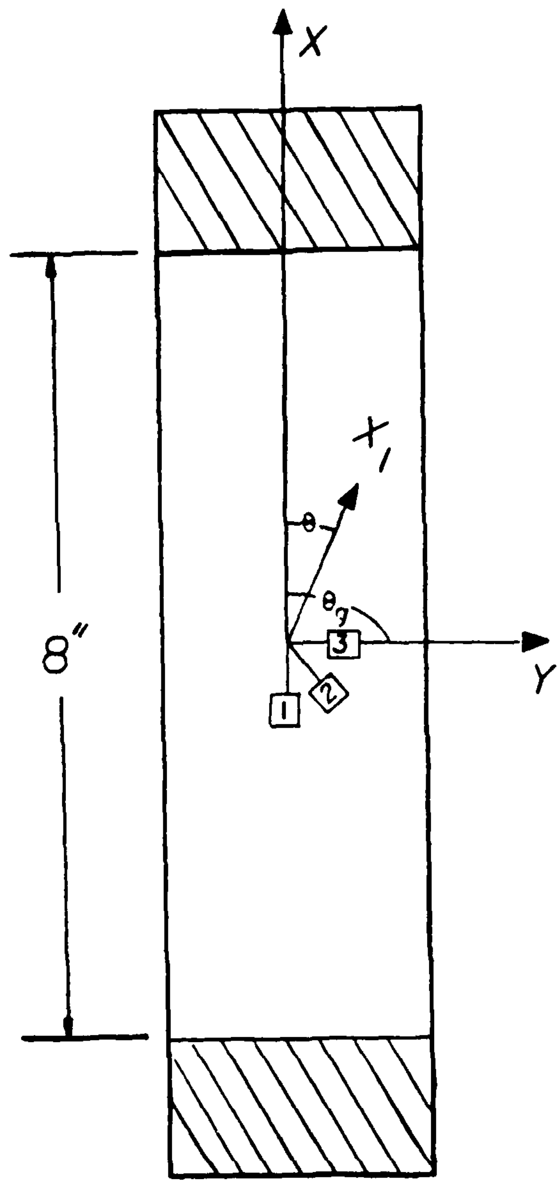

Figure 9 Specimen geometry and strain gage arrangement for modulus and strength measurements